INTEGRATION OF AN ELECTROMAGNETIC GUN POWER SUPPLY INTO A SHIP POWER SYSTEM

Report

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MISSION STATEMENT

The Electric Ship Research and Development Consortium brings together in a single entity the combined programs and resources of leading electric power research institutions to advance near- to mid-term electric ship concepts. The consortium is supported through a grant from the United States Office of Naval Research.

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1 EXECUTIVE SUMMARY

While the development of electromagnetic gun technology continues, so does improvement of the power systems in future Navy ships. This investigation reviewed the work in both areas to assess the likelihood of compatibility of the two in the future. From the available data, it appears there is growing compatibility.

At the conceptual design level, it appears that good compatibility is likely. It is probable that a specific point design today may require some less than ideal choices. The ongoing research, however, will likely broaden the design space in the future.

The important more detailed observations from this investigation include:

- Storage is required at the EM gun for efficiency and size of the ship power system and to be able to control the required large rates of change in the gun current.
- Capacitors, batteries, and rotating machines are likely to be the storage options of choice.
    - From size and weight considerations, batteries and rotating machines are fundamentally preferable.
    - From the perspective of experience with EM guns, capacitors and rotating machines are good candidates.
    - Acceptable capacitors and rotating machines can be built today. There are likely still improvements needed in battery system power and energy density, as well as opening switches before a battery system can be built.
    - Research is improving all of the technologies.
- The storage required for the EM gun can be integrated into the ship power system to provide power quality improvements, ride-through capabilities in the event of temporary loss of generation capability, and power for other pulsed loads when the EM gun is not needed.
- The EM gun storage will likely augment rather than displace all other storage in future electric ships.
    - Ship power systems can likely benefit from some distributed storage.
    - The electromagnetic gun storage must be concentrated near the breach of the gun.
    - The concept of operations will likely require simultaneous use of more than one energy storage system.
- Control of the arc flash, associated with the projectile exit, is needed for grounding reliability and to improve system efficiency.
    - Demonstrated technology to accomplish this is available.

2 INTRODUCTION

Electromagnetic (EM) guns provide potential benefits over conventional gun powder weaponry. Key benefits among these are improved lethality and range. Kinetic energy projectiles can efficiently defeat current targets and show potential to defeat future targets while reducing collateral damage. Another advantage is a smaller logistics trail. The propellant is the ship's fuel; it does not need to be supplied with each projectile. This attribute of the system highlights another advantage, i.e. reduction of on board energetic materials. Moreover, with the appropriate design, there can be a significant reduction in launch signature. Finally, the reduced time of flight can increase operational tempo while providing greater stand-off distances to improve self-defense.

The fundamental concept of an electromagnetic gun is shown in Figure 1. At the upper right are two rails that can be viewed as serving the function of a barrel in a conventional gun. In a conventional gun, the "U"- shaped projectile would be accelerated by the expanding gases from an explosive charge. In this case, however, the force is a Lorentz force resulting from the magnetic field produced between the rails due to the current in the rails and the same current flowing through the projectile. The force is given as

$$F = \tfrac{1}{2} L' I^2 \qquad [1]$$

where L' is the inductance per unit length of the rails and I is the current through the projectile[1]. A key conclusion from Equation 1 is that for any gun with its particular geometry, the force and, therefore, the velocity of the projectile is determined by the square of the current passing through the rails during launch. The inductance gradient L' has limited variability for a simple two rail system, which is preferred for its simplicity and efficiency.

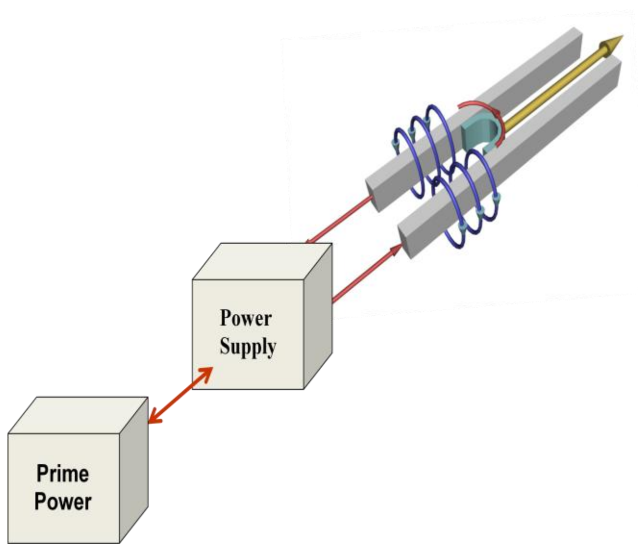

Figure 1: Notional diagram of an electromagnetic gun

Since there is a need for very high power during the launch, some form of energy storage is inherent in any electromagnetic gun system. The reason for storage is that it permits the prime power system to be smaller, lighter, and operate more efficiently than it would if it had to be designed to provide the peak power for the gun. In Figure 1, this energy storage is part of the block marked "Power Supply." The power supply also includes necessary control, power conversion, and thermal management systems.

The individual shots can require in excess of tens of megajoules of energy at the breech of the gun and require peak powers in excess of 1 GW. Consequently, the storage must be located relatively near the breech of the gun to minimize the inductance and losses due to resistance. The operating current is of the order of 10^6 amperes. The gun also requires a sharp rate of rise of current. Minimizing inductance is essential in keeping the voltage drops small under these conditions. Minimizing the resistance has clear advantages for efficiency. Conventional solutions for these challenges are to use multiple conductors and short connections between the storage and the breech. Various combinations of these approaches will work, but size and weight limitations typically favor close proximity between storage and the gun breech.

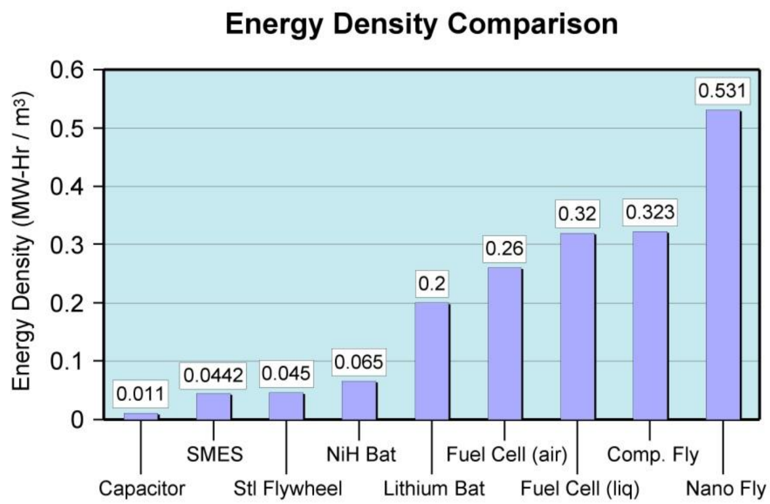

Figure 2: Comparison of the energy density for various energy storage technologies.

While the electromagnetic gun physics constrains storage location, the storage can potentially be used for other applications depending on the concept of operations. This is particularly true for loads that require longer pulses with slower rise times or to maintain power during switching operations. So, the storage system for the electromagnetic gun can have multiple uses when properly designed and controlled.

All of the energy for the launch of a projectile ultimately comes from the fuel in the vessel. Depending on the assumed energy content of the fuel used as well as the overall system efficiency, one should expect to get a launch of about 10 MJ muzzle energy per gallon of fuel. This could be equivalent to a number of low energy shots or a fraction of a higher energy shot.

3 Storage Technology Options

The primary energy storage technologies used on ships today are capacitors, rotating machines, and batteries[2]. Electromagnetic guns have been successfully operated using each of these storage technologies. In addition, significant laboratory research and development on launchers and launch physics were performed using inductive storage[3]. So, the Navy is in the position that it has a choice of storage technologies. Since all of the technologies work well, the choice is likely to be driven by factors such as the naval platform, size, weight, first cost, and life cycle cost.

The Navy land-based electromagnetic gun research is being done with capacitors as the storage technology. While capacitor storage is one of the established technologies for this application, Figure 2shows that the energy density of capacitors is about an order of magnitude less than that of batteries or rotating machines. This is frequently not an issue for testing in a laboratory, but may become a concern for applications in which space and weight are at a premium. It should be emphasized that the uncertainty in the information in Figure 2 is likely +/- 1 in the most significant digit. The rather large uncertainty is due to the fact that the particular application can dictate the details of the storage system. This chart is an effort to provide a notional comparison, not a definitive set of distinctions. The individual values are accurate reflections of the values calculated for the point designs examined.

The technologies naturally divide into four classes. Passive components, like capacitors and inductors, have the lowest energy density. Older technologies like steel flywheels and NiH batteries are better than passive components, but are still low. The SMES (Superconducting Magnetic Energy Storage) is an older technology that has not advanced in energy density, largely due to the necessity of field cancelling so that people can safely work in the vicinity of the system.

The next class of comparable devices contains lithium ion batteries, fuel cells, and composite flywheels. Fuel cells are not attractive technologies for power supplies for electromagnetic guns because they are fundamentally too slow. In a fuel cell the reaction takes place at the surface of the electrodes instead of within a volume. A fuel cell is designed to maximize the electrode surface area. This design necessarily makes for smaller pathways for the transit of the reactants; and so, rather than bulk transit mechanisms, diffusion mechanism control the speed at which reactants can be brought to the system, thus limiting their rate. Batteries are also limited by diffusion and chemical reaction rates. In this case, however, researchers are attempting to minimize these effects over relevant time scales through battery chemistry and lower impedance architectures. So, while both are affected by similar processes, battery development will likely determine whether or not these inherent limitations can be overcome.

The final level is the future promised by advances in nanotechnology. Carbon nanotubes are showing promise for longer and longer fibers[4] that may eventually be able to replace the conventional carbon fibers used today. Similarly, adding carbon nanotubes to the resin in the composite[5] is yielding enhanced performance. The use of carbon nanotubes for stronger composites holds promise but significant challenges in manufacturing the fibers and composites remain.

Although not highlighted in Figure 2, nanotechnology is also promising to improve battery performance. For example, materials research suggests more rapid charge and discharge times[6] and longer cycle life may make batteries even more appropriate for high power applications in the future[7].

The discussion has been in terms of energy density, which is appropriate, because the stored energy is an indication of how many shots can be fired without recharging, which is an important factor in repetition rate. For pulsed applications, power density is also very important. This is particularly true because electrochemistry limits the power density, so assemblies of batteries frequently have excess energy storage to meet the power density limitations. This attribute puts a minimum size limit on a system. If that limit is appropriate, however, the excess energy storage can be used for more shots or other applications on board. A reason, however, that research in nanotechnology is trying to reduce charge and discharge times as well as increase cycle life is to make a battery a more attractive pulsed power source.

From size and weight considerations, it appears that batteries or rotating machines will likely be the long term storage solution. Batteries have a long history in submarines. From the perspective of maturity of appropriate technology, capacitors and rotating machines are likely nearer term solutions. Capacitor powered systems may be used in early proof-of-principle demonstrations, because of the experience gained with these systems in the development program. Rotating machines are the motors and generators on ships. Moreover, the new electromagnetic aircraft launch system, being installed on carriers, uses rotating machines for storage[8] for the high power pulsed load.

3.1 Granularity of Storage

All of the important approaches to storage technology are granular. Therefore, the storage system is comprised of a number of discrete, nearly identical components. Thus, granularity is beneficial for good design, but when the granularity is imposed by the technology rather than being a choice of the designer, alternative solutions must be investigated.

Batteries have a minimum fixed level of granularity, a single cell. The cell voltage is fixed when the battery chemistry is selected. The voltage of a single cell is typically < 5V and is a fundamental consequence to the dominant electrochemical reaction. Typical bus voltages will be in the range of 500-1000 V indicating the need for several of these cells, 100-200, connected in series to build up to a voltage sufficient for a dc bus. In addition, several of these strings of cells in series are used in parallel to build up to the required current, and therefore power level, especially for high power applications and to build up the required energy for the lower power applications. Practical integration factors, such as bus work, mounting, maintenance access, monitoring and cooling systems increase the system volume so the energy density of a large system is much less than that of a single cell. An example of this is shown in Figure 3(a) and (b), which show two views of the 5 MW lithium ion storage system built by Portland General Electric in Oregon for the Pacific Northwest Smart Grid Demonstration Project[9].

Reliability is another issue of significance when the number of cells required reaches the thousands. The failure of a single cell can fail an entire series connected string and can lead to a cascade failure as the load shifts to parallel strings and increases their discharge rates. Safety is also a concern with shipboard applications with a large array of batteries. Li-ion batteries have a demonstrated catastrophic failure mode [10]; they are extremely sensitive to overcharging which then requires a complex battery protection system to mitigate that problem which further reduces the overall energy storage density. Recently, non-flammable electrolytes have been introduced in $LiFePO_4$ batteries [11]; however, these batteries have a 30% lower energy density relative to the previous generation.

(a) Single aisle of batteries (b) External view of facility

Figure 3 (a) and (b): Internal and External View of a 5 MW Lithium ion energy storage facility in Oregon

Rotating electrical machines can be designed to the specific granularity needed for the application. Motors on ships, for example, range from a fraction of one horsepower for small servo motors to thousands of horsepower for propulsion. The granularity is chosen by the designer to be optimal for the application. Having several flywheel/generators rather than a single large one is beneficial from the sheer size and practicality of fitting it in a given volume within a ship. This is particularly significant if one imposes the prudent requirement of replacement via standard hatches. Multiple independent units can provide redundancy and the associated fault tolerance. Beyond this, there is an economy of scale which drives one to relatively few larger units. Thus, the granularity in the case of rotating machines can be optimized for a given application.

Figure 4 shows a single pulsed alternator connected to the ship's grid. Since the railgun is an extremely rarely used load, the energy stored in the rotor of the pulsed alternator is available for load leveling duty through the motor/generator, for the majority of the time. Exploiting this type of dual usage is of great value, considering usage of available space and money invested. It must be noted that the high energy density capacitor system cannot store energy for any prolonged length of time without severely limiting its life and, therefore, cannot be put to this dual use.

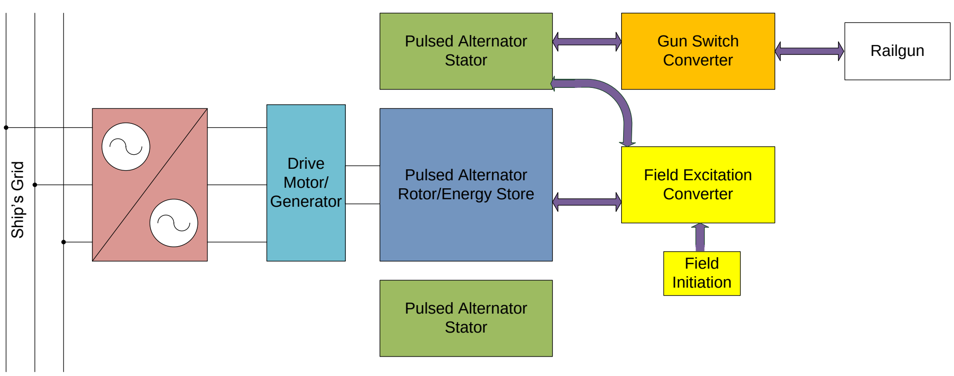

Figure 4: Pulsed alternator shown with related components connected to the ship's grid

It is recommended that pulsed alternators be used in pairs (Figure 5). The pair is counter rotating to compensate for gyroscopic effects and to compensate the torque of the EM gun between the two machines and, thus, have little torque transmitted to the ship's structure. Adherence to this design principle implies that most applications will use an even number of machines.

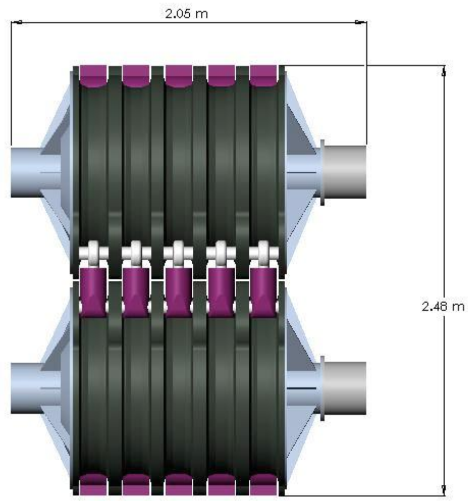

Figure 5: A pair of pulsed alternators that are counter rotating and manage the torque between them

This approach works, of course, only if the pulsed alternators can be synchronized to operate in parallel. Fortunately, it has been demonstrated both experimentally and theoretically that such operation is possible. Each machine can easily generate the necessary voltage to drive a railgun to interesting velocities; however, the current produced by each machine must add up to the value required by the gun, for which they need to be in phase and discharge in parallel. Figure 6 shows a system of 4 pairs of pulsed alternators described in [12].

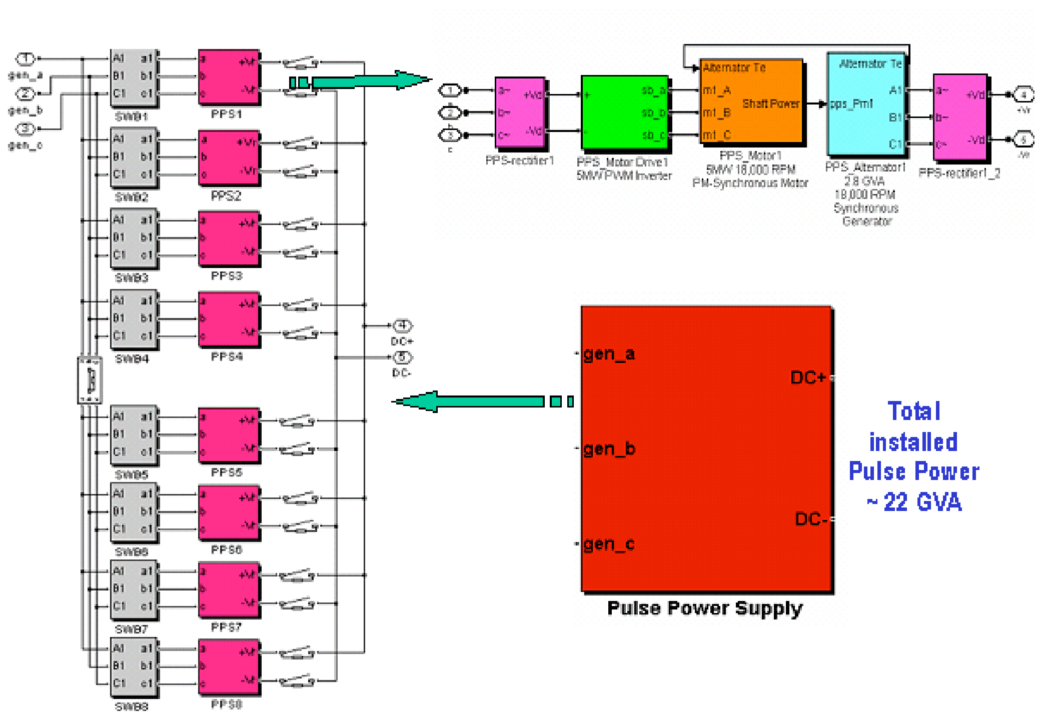

Figure 6: Circuit model of a pulsed load being driven by four pairs of pulsed alternators

A report[13] submitted to the Army in 2003 investigated the operation of multiple pulsed alternators. Different schemes were investigated for the manner in which the machines are connected. For example, the field coil could be connected in series or parallel even though the main discharge pulse into the gun has all the machines in parallel. The series connected field coil has the advantage that the current in the field coil of the machines is the same, thus, ensuring that the voltages in the armatures are also the same. Then, there is also the option of connecting the machines in parallel at the dc side of the rectifiers or the ac side. One could connect the machines on the dc side beyond the rectifier, however, then the self-correcting circulating currents between the machines are blocked, thus, preventing the machines from re-aligning (as they do in conventional machines) in phase. The recommended manner for connecting the machines is shown in Figure 7.

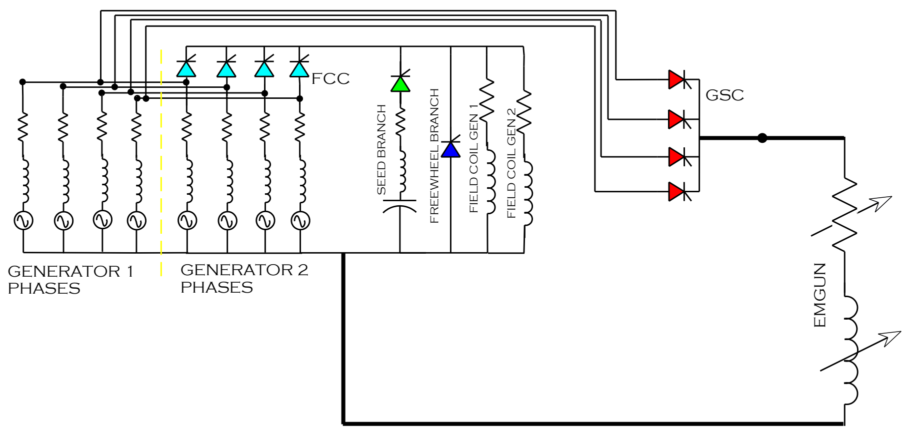

Figure 7: Recommended method of connecting machines in parallel for multiple machine operation

It was assumed that the machines were the same and then allowances were made for slight differences in the resistances and inductances. Then, initial offsets in the phase angle were introduced to account for tolerances. Thereafter, simulations were performed with the initial conditions that the machines were brought to full speed with the initial phase offsets (≤ 2° electrical). The field coil was charged and then the EM gun was energized. Simulations indicated, despite of the offsets in phase and parametric values, the machine performed as expected with minimal offsets introduced by the discharge.

The key to being able to operate these machines in parallel is the motoring system that maintains the speed and phase lock during motoring from zero to full speed and then re-engaging after the discharge to re-align and re-accelerate the machines. This motoring system was also simulated and performances before and after the pulse did well. The motoring system used an induction motor and a motion controller that generated a master speed and phase profile that the two motors were required to follow to stay in lock step.

This modeling and simulation theory was put to test under funding from the Navy. Since two air core machines were not available, two 50 kW, three phase, conventional machines were used to test the basic principles. The machines were of identical ratings and from the same manufacturer. These are shown in Figure 8. The field coils in these machines were connected in series and excited externally through a dc source. The motoring system and motion controller were obtained from as a custom built unit from Baldor, which used the same master-slave approach for the speed and phase angle control as described earlier.

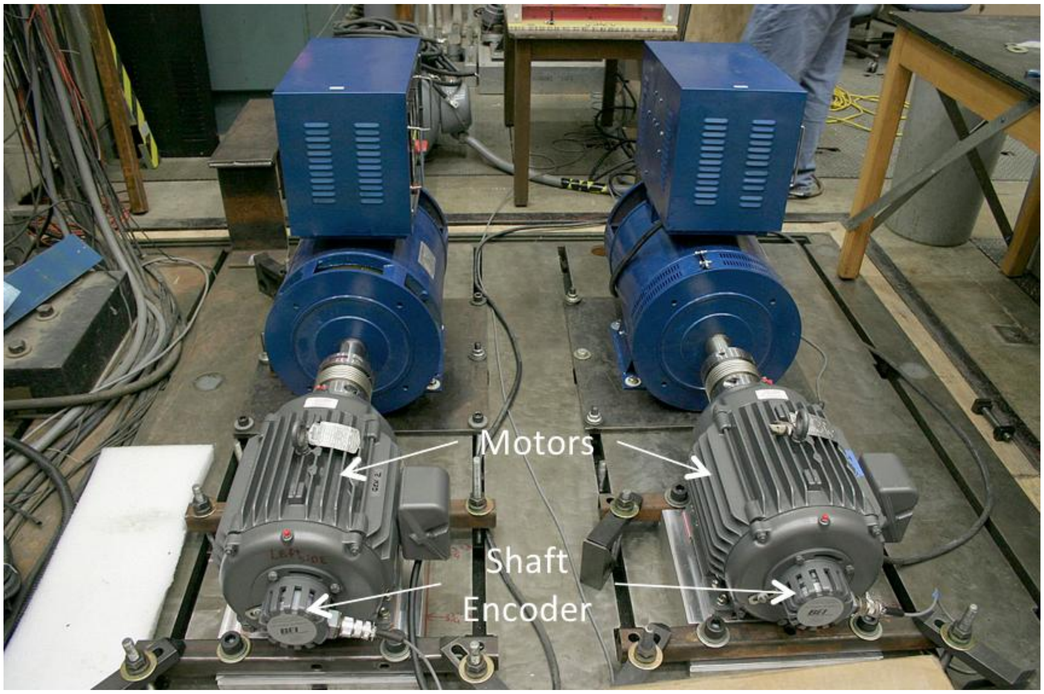

Figure 8: Two 50-kW generators with motors and shaft encoders for discharge and synchronizing tests

The circuit set up for the tests is shown in Figure 9. The corresponding phases of the two machines were connected on the ac sides, before the SCRs. Figure 10 shows the typical speed time profile which shows excellent synchronization between the two machines. The field coil is turned on just before discharge. Soon after, the machines are freewheeled. Thereafter, at 0 seconds the discharge takes place and then the field current is turned off around 8 seconds. So long as the field current is on, the machines stay in lock step due to the current sharing between the machines. Despite introducing the 1°-2° phase errors the current sharing between the machines stayed fairly close.

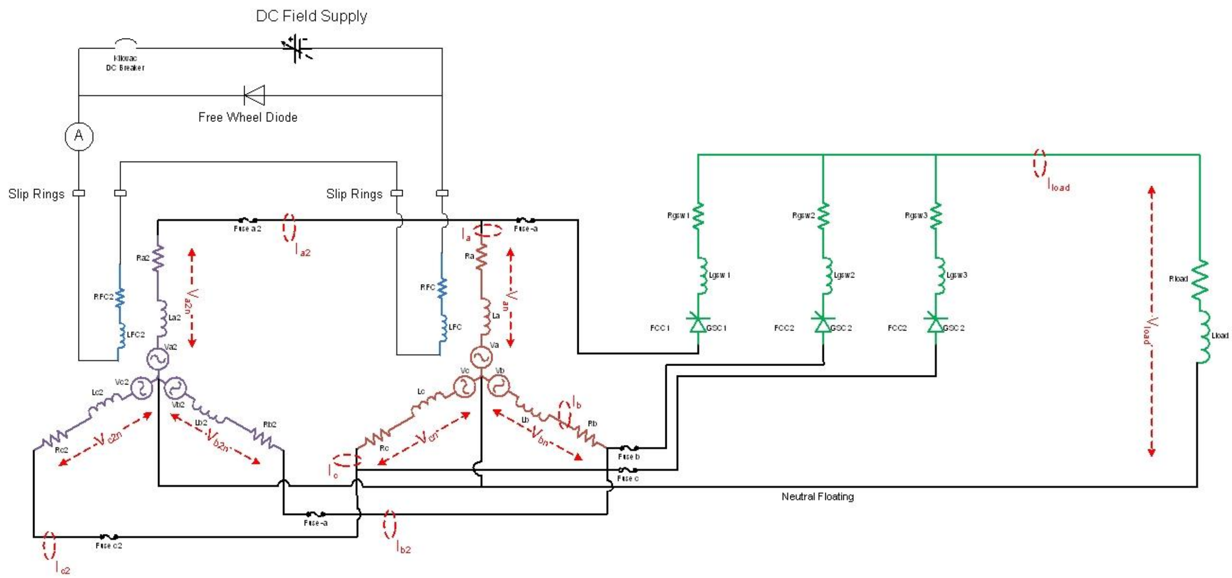

Figure 9: Circuit set up for the tests of the two 50 kW machines with the measurements

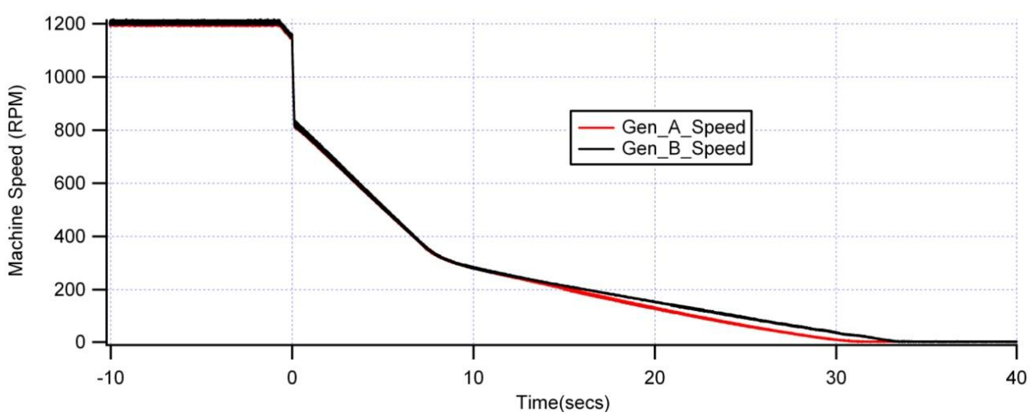

Figure 10: Speed versus time profile - the two machines are freewheeled and discharge initiated at 0 s - field current is switched off at around 8 s.

3.2 Integration with Ship Power Grid

3.2.1 Charging Effects on Ship Power Systems

The gigawatt pulses required by an EM gun launch cannot come directly from the ship's power system, but all of the energy in these pulses will be provided by the ship power system. So, energy will need to be stored in one of the three likely technologies to produce the required high power pulses. However, most of the weapons systems are rated for repetitive duty and some of them have fairly high repetition frequencies. This means, the energy store will need to be replenished in the interval between pulses.

This is a significant consideration for capacitors, because with the present energy density of the capacitors, storing multiple shots, as in a salvo, would result in a very large and heavy storage system. Secondly, high energy density capacitors degrade very rapidly when held at voltage for prolonged periods. Rotating machines, on the other hand, can store a few shots and EM gun systems storing multiple shots have been built and tested. Similarly, batteries can store multiple shots, in principle, but this has not yet been demonstrated by direct powering of EM guns with batteries.

Whether it is a single shot or a salvo, the storage system will be replenished using the ship power. The replenishment power levels can be in the several tens of megawatts. Several studies have been reported on the effect on power system stability when large power is drawn from the ship's grid [14, 15,16]. Typically, the prime mover speed control system, which involves fuel control valves and the combustion process, is relatively sluggish. The result is that immediately after the power draw increases, the energy that is required comes from the inertia of the rotor. It slows under the influence of the higher torque produced by the increased load. This results in a frequency droop and a voltage droop. There are power quality constraints that need to be met so that sensitive equipment does not malfunction, one of these requirements is that the frequency needs to be maintained within a very narrow range (±3%). This limits the amount of energy that can be drawn from the generators.

The higher the inertia of the generator, the better is its ability to handle these transients. Given that while the prime mover is catching up with the new load conditions, energy to the load comes from the stored energy in the system, such as the rotors of the generators. Then, increasing the stored energy in a system via flywheels or batteries would help stabilize the system under these extraordinary power draws. These storage devices can respond very quickly to the increased demand, as the only time delays are those associated with the switching of power electronic devices.

The Navy is, therefore, considering storage devices, such as batteries for lower power applications and flywheels for higher power needs, through its Hybrid Energy Storage Program. With an appropriately designed storage system on board, the ship's power system can be made to operate at a relatively constant power level and all fluctuations around this average are either absorbed or delivered by the storage devices. The power control system will need to be able to demand the correct level of power at the appropriate time from these storage devices. Besides improving the stability of the grid under pulse power loads it may also be an efficient way to operate the ship's power.

3.2.2 Stabilizing Effects on Ship Power Systems

The stored energy in an EM gun system can provide the grid with ride-through power during transient power fluctuations. Here, the focus is on the discharge into the grid. There has been significant research performed modeling ship power systems using Matlab/Simulink [15,16,17]. These models captured a good amount of the detail of a ships power system, as seen in Figure 11. It included the energy storage flywheel and its control, the generator-turbine and its control, and fairly good representative load. Including the turbine and its speed control loop is essential to capture the frequency and voltage sags that may be experienced. This study showed that in case there was a generator outage the control system would allow power to be drawn from the flywheel energy storage. The outage was initiated at 0.75 s. Figure 12 (a) shows that the power system voltage and frequency is not perturbed significantly during this switch of power sources due to the outage. Figure 12(b) shows the currents in the various parts of the system. The generator current is cutoff and the flywheel currents rise to meet the needs of the load. The small bump in the DC bus current is related to the passive elements, such as filter capacitors being charged.

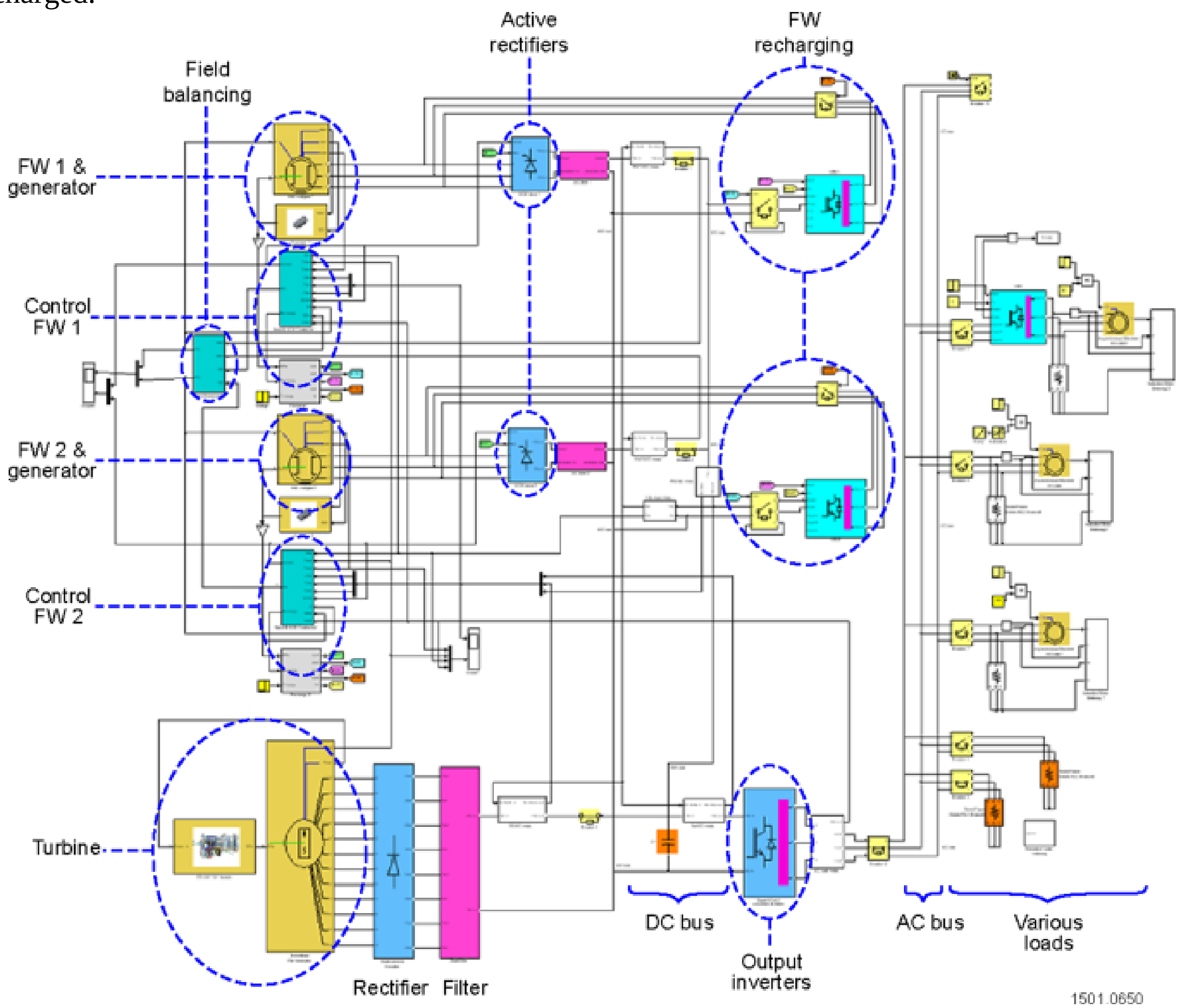

Figure 11: Typical ship power system with representative loads and energy storage

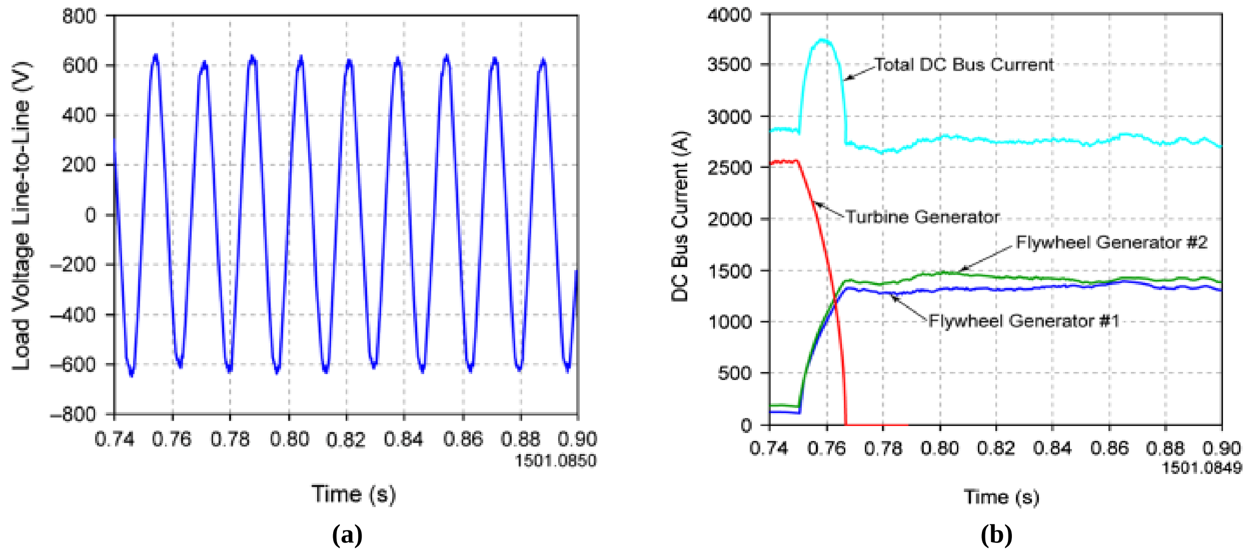

Figure 12 (a): Load voltage during transition to stored energy source; (b): Currents in the various parts of the circuit during the transition

Another study considered using pulsed alternators instead of capacitors to drive the EM gun [18]. The pulsed alternators store energy in the rotor similar to what is done for aircraft launch in the EMALS system. This study considered using the energy that is stored for EM gun launch for other grid stabilization tasks, such as when driving other pulsed loads on the grid, e.g. a free electron laser (FEL), and injecting harmonics in the gird to reduce the total harmonic distortion (THD). The energy store was shown to perform these tasks adequately. To demonstrate the sharing of the stored energy amongst other high power loads, the following operational scenario was used: 1) accelerate the ship from rest to full speed, 2) reduce the ship cruising speed to release power for EML energy storage system, 3) charge EML energy store, 4) fire EM gun, and with the remaining charge 5) fire burst of 4 FEL pulses.

This represents a realistic operational scenario in which the ship is providing over the horizon support with EM guns and is subjected to a missile attack, which is being countered by the FEL. The energy store for both the EM gun and the FEL is common and Figure 13 shows the energy stored in the rotors and the energy used by the two pulsed loads. This research showed that making the power from the energy store available to the EM gun on one side and to the free electron laser through the main bus can make use of available energy stored more judiciously, as opposed to providing independent storage for each pulsed load.

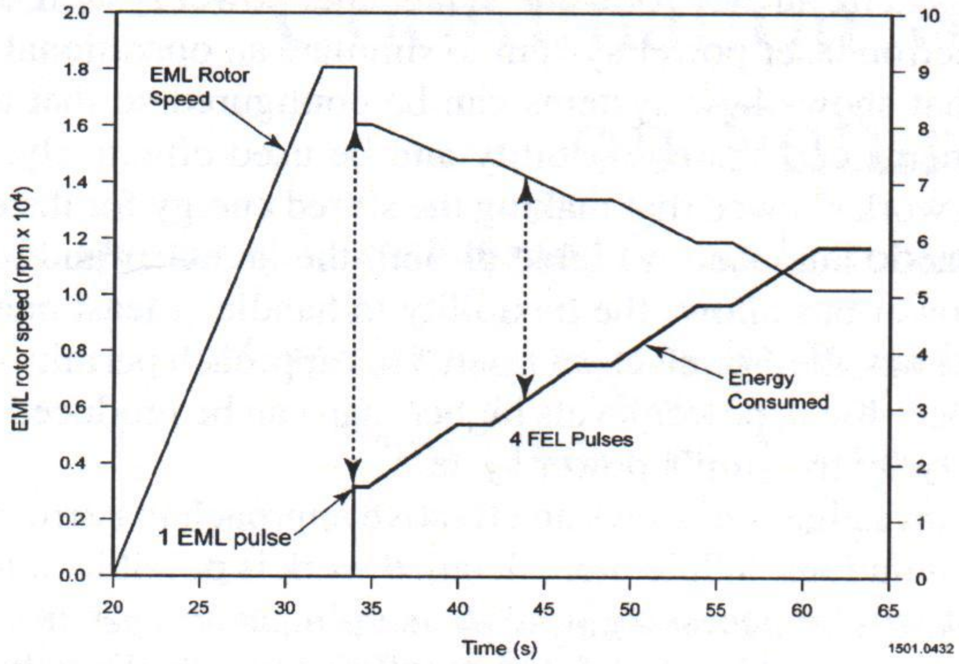

Figure 13: Energy stored in rotor and energy used by the components

3.2.3 Sharing of Storage for Multiple Pulsed Loads

It is clear that future electric ships will have a variety of offensive and defensive systems that will use short bursts of relatively high power such as EM guns, lasers, and active denial systems. It would be very wasteful and impractical if the ship prime power system was designed to handle this total peak power, as the majority of the time it would be operating at a fraction of the installed power. This implies that energy storage will be required, which would allow bursts of high power to be extracted while the prime power system is operating at a nominal, but level power. One approach would be to have independent storage for each pulsed power system, but a more prudent approach would be to design an energy storage system that could be used for all the pulsed loads, thus, minimizing components, spare parts and maintenance items. Besides driving the pulsed loads this storage system could provide ride through power while a spare turbine is being brought on line or a distribution bus is being re-configured to isolate a fault. Other uses as described in [18] are injection of harmonics into the grid to improve power quality by elimination of harmonic currents. Sharing of the pulsed power by various pulsed loads is achieved through a grid. Whether the pulsed grid is isolated from or integral with the main grid is dependent on the specific combination of loads for a particular platform. There should also be the possibility of connecting the pulsed grid to the main grid if it is isolated. However, placement of the pulsed sources will be important too. The pulsed sources should be placed closer to the higher power pulsed loads thus minimizing the cabling and bussed to the lower power pulsed loads.

Therefore, it is imperative to choose the energy storage technologies very carefully, as some of these storage technologies, as described earlier, preclude this dual/shared use. High energy density capacitors are one such technology that cannot be used for long term storage because of the degradation of the capacitors when they hold charge for extended periods.

3.3 Unique Electromagnetic Gun Implications

3.3.1 Grounding

During the discharge of the railgun, the main power bus is isolated from the pulsed power and is, therefore, unaffected by it. That is true only with appropriate grounding. Unless grounding is addressed carefully, the muzzle arc at projectile exit could couple the pulse power into the main bus and cause over voltages in the main power system. The EM gun is one of those loads where the currents are very high and the currents may not always follow the anticipated path. The path can change from shot to shot because any muzzle arc at the end of the barrel will take a random path from one shot to the next. Figure 14 (a) shows a normal muzzle arc at the end of a barrel formed at projectile exit.

The currents in this arc can be as large as several hundred kiloamps. Figure 14 also shows the "negative" rail as grounded. Figure 14(b) shows the muzzle arc coupled to the ground through some alternate path, which could be instrumentation, a cable, or other equipment. This current from the muzzle arc then finds its way back to the pulsed power supply through an unanticipated path and cause substantial damage. It could also result in what is called ground bounce, which is a term from driving the potential of the local ground to be different from the general ground on a transient basis. This can damage critical components in the control system. Therefore, it is desirable not to ground the pulse power output. Without the ground, even if the muzzle arc couples to some equipment, unless there is a second ground fault, the high current does not find its way into delicate equipment. If this grounding is required for personnel safety during maintenance, it can be switched in after the power to the gun is switched off.

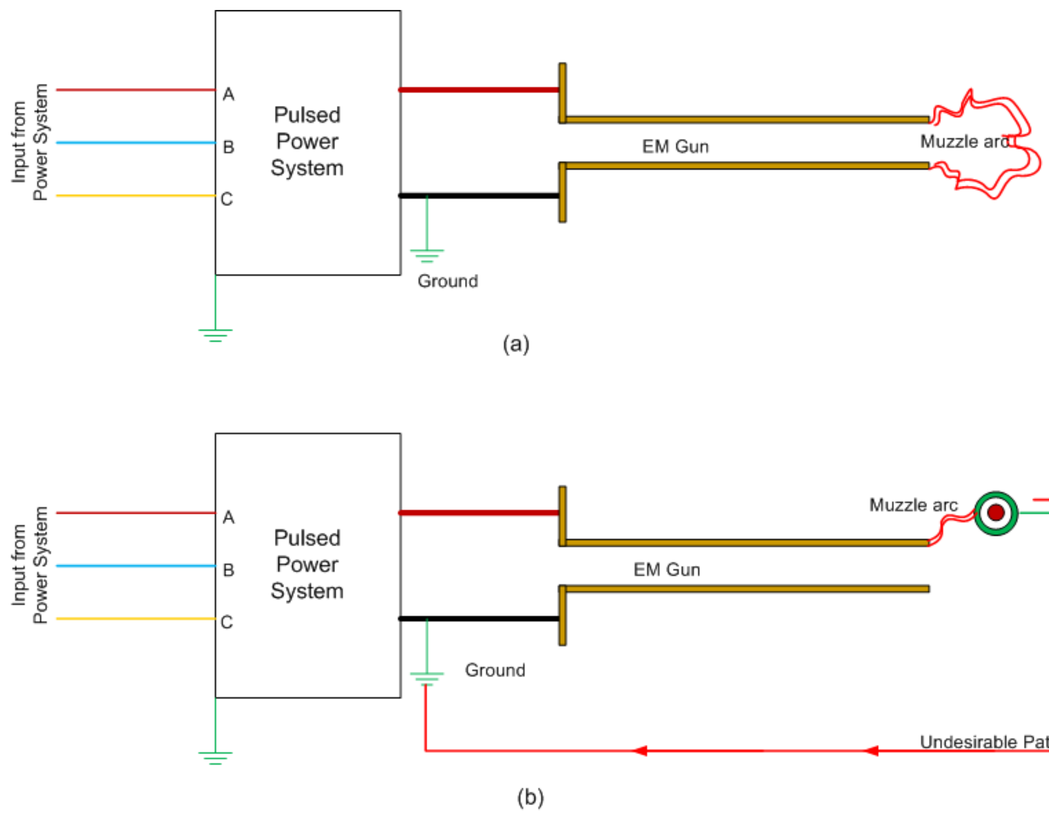

Figure 14 (a) and (b): Showing potential problems when the pulsed power output is grounded (a) normal muzzle arc (b) muzzle arc couples to ground via a cable, instrument or other equipment

3.3.2 Energy Recovery and Effects on Power System Design

Figure 15 shows a typical current pulse from a capacitor pulse forming network when driving an EM gun[19]. Note the point of projectile exit at 8m. Typically, the current at exit is about 50% of the peak current. This is a substantial amount of current and represents two problems. One problem is wasted energy and the second is a muzzle arc which could destabilize the projectile. Moreover, the management of a muzzle arc requires sacrificial arc horns that need to be replaced periodically. The muzzle arc also produces a bright signature flash, and as aforementioned, could result in ground currents. These problems have been recognized and a straightforward mitigation approach involves the use of a simple muzzle shunt. A muzzle shunt is an alternate path at the end of the barrel where the current commutates after the projectile exits. At that point, the magnetic energy that was residual in the barrel at the projectile exit is trapped in the barrel where, unless it can be removed from the barrel, it will simply cause heating in the barrel and the muzzle shunt. Proper design permits the removal and reuse of the energy reducing the thermal management challenge and making the system more efficient.

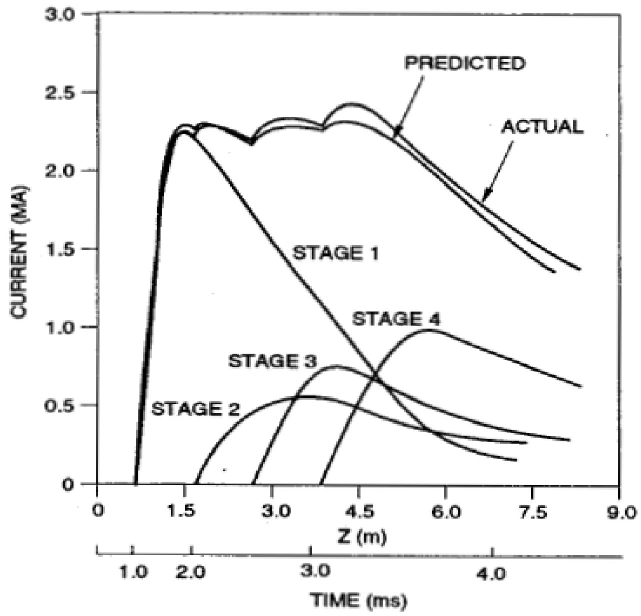

Figure 15: Staged discharge of a pulse forming network into an 8 m. gun - note large current at exit (8m.)

As an example of appropriate design with the pulse alternators, the energy can be reclaimed into energy storage. To accomplish the reclamation, the red SCRs in Figure 7 are triggered closer to zero phase voltage so that the current commutates into a phase that is about to go negative in voltage. During this negative voltage half cycle, the energy is reclaimed out of the barrel and returned to the store. This is shown in Figure 16. With the pulsed alternator, there is another component where the energy is reclaimed after completion of a shot; this is the field coil energy. Being an air core machine, there is a substantial amount of energy stored in the field coil of the pulsed alternator. The energy is needed so that the voltage can be generated in the armature winding. This energy is reclaimed at the end of a shot and stored back into the rotor.

Besides being an efficient way of operating a system, reclaiming energy stored electrically also helps to minimize the thermal stress on the components. An added benefit is that the power needed from the ship's power system is reduced as the amount of energy that is needed is reduced between shots. The ship's thermal and power management benefit from the improved efficiency.

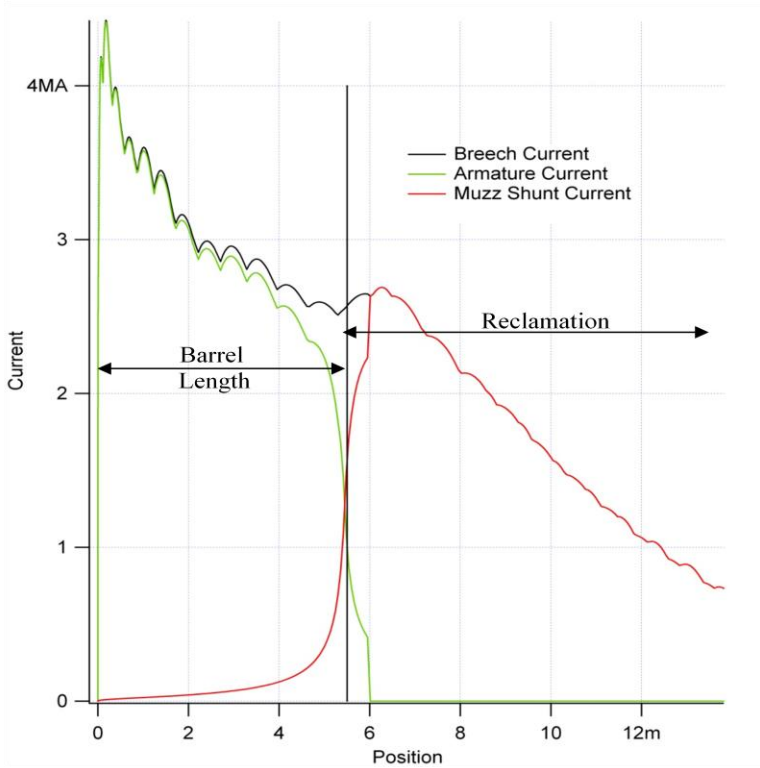

Figure 16: Reclamation of the barrel energy at the end of a launch with a pulsed alternator system

3.3.3 Opening Switches

Batteries have higher energy densities than capacitors and are roughly comparable to rotating machines, considering all auxiliaries. Batteries, however, are power limited. Due to this limit on power density, they are not being used to directly power a railgun; this is true even after considering the recent developments in improving their power density. Some researchers[18] have returned to proven pulse compression techniques, applying them to modern batteries and inductors. Inductive storage has been used in conjunction with homopolar generators in the past[19] to drive railguns. Like homopolar generators, batteries benefit from an inductor as intermediate storage so that the energy from the battery can be stored in the inductor at relatively lower power and then with the aid of an opening switch, this energy can be transferred into a gun at relatively higher power. The inductive store has a higher energy density than capacitors but not as high as rotating machines.

The challenging component in an inductive storage system is the opening switch, which needs to be fast acting. The solution in the past has been to use explosive driven switches, which were then simply single shot switches. The effort in [20] describes an attempt to use solid state (IGCT) switching with energy recovery from the inductor during the opening process and re-using that energy to accelerate the projectile. Experiments have been performed using this technique on a small 0.56 m railgun at modest current levels of tens of kiloamps. It remains to be seen if this can be done at high current levels of interest to Naval EM gun systems. However, if successful, the use of solid state switches repetitively could be beneficial to making inductive storage an option for railguns.

4 CONCLUSIONS

The primary conclusion from this investigation is that there are options for the integration of an EM gun into a ship power system and no obvious show stoppers. While many of the required technologies have been tested, advances are continuing.

The important more detailed observations from this investigation include:

- Storage is required at the EM gun for efficiency and size of the ship power system and for the ability to control the required large rates of change in the gun current.
- Capacitors, batteries, and rotating machines are likely to be the storage options of choice.
  - From size and weight considerations, batteries and rotating machines are fundamentally preferable.
  - From the perspective of experience with EM guns, capacitors and rotating machines are good candidates.
  - Acceptable capacitors and rotating machines can be built today. There are likely still improvements needed in battery system power and energy density, as well as opening switches before a battery system can be built.
  - Research is improving all of the technologies.
- The storage required for the EM gun can be integrated into the ship power system to provide power quality improvements, ride-through capabilities in the event of temporary loss of generation capability, and power for other pulsed loads when the EM gun is not needed.
- The EM gun storage will likely augment rather than displace all other storage in future electric ships.
  - Ship power systems can likely benefit from some distributed storage.
  - The electromagnetic gun storage must be concentrated near the breach of the gun.
  - The concept of operations will likely require simultaneous use of more than one energy storage system.
- Control of the arc flash is needed for grounding reliability and to improve system efficiency.
  - Demonstrated technology to accomplish this is available.

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